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Is the Universe rotating?

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From the study of the position angles and polarization of high luminosity classical-double radio sources, it appears that the difference between the position angles of elongation and of polarization are highly organized, being generally positive in one half of the sky and negative in the other. The effect was first noticed amongst a sample of 94 3CR sources and later confirmed in three independent samples. Such a phenomenon can only have a physical explanation on a cosmic scale; an attractive theory is that it demonstrates the existence of a universal vorticity, that is, that the Universe is rotating with an angular velocity $\sim 10^{-13}$ rad yr^{-1}. This would have drastic cosmological consequences, since it would violate Mach's principle[1,2] and the widely held assumption of large-scale isotropy.

A complete sample of 94 3CR radio sources in the declination range $15° < \delta < 40°$ has been observed at Jodrell Bank at four wavelengths; detailed polarization results are to be published elsewhere. These results include values of Δ, which is the position angle of the magnetic field vectors minus the position angle of elongation of the source (the major axis); obtained for 45 of these sources (Table 1*a*). The sources, ordered in right ascension (RA), fell into two groups divided at RA 0915 and 2115, in which the sign of Δ became, in sequence:

Sample 1: ‒‒‒‒‒++‒‒‒‒‒‒‒+‒‒‒‒‒+‒ 4(+), 18(‒)

Sample 2: ++++++‒+++‒‒++‒+‒+++++‒+ 17(+), 6(‒)

The difference between the two was striking, and prompted further analysis of the data; even taking account of the arbitrary division in RA, this result was already significant, the χ^2 test for two degrees of freedom yielding a significance level, $\alpha = 2.6 \times 10^{-3}$ (that is, the probability that the difference between the samples was due to chance was $\leq \frac{1}{4}\%$).

If the magnitude as well as the sign of Δ is considered the following mean values are obtained:

$$\text{Sample 1:} \quad \bar{\Delta}_1 = -31.6° \pm 8.0°$$

$$\text{Sample 2:} \quad \bar{\Delta}_2 = +12.3° \pm 7.3°$$

These differ at the significance level, $\alpha = 2.5 \times 10^{-4}$. The quoted uncertainties are $\Delta_{r.m.s.}(N-1)^{-\frac{1}{2}}$ where $\Delta_{r.m.s.}$ ($\simeq 35°$) is the root mean square deviation from the mean of the values of Δ and N is the number of sources in each sample. The spread in Δ is mainly intrinsic, only $\sim 10°$ arising from uncertainty in the individual values.

The values of Δ in Table 1*a* were derived by averaging the values obtained for the outer components of each source; in general, these agree with the values derived from the integrated polarization alone, for which the effect is present at a similar significance level, $\alpha = 4.6 \times 10^{-4}$. The polarization data, and the values obtained for the intrinsic position angle of the magnetic field, agree well with previously published measurements[3,4], and according to accepted criteria[3,5] there was no ambiguity in the rotation measure fits for the 45 sources for which values of Δ were obtained, all ambiguous cases (there were 10) having been rejected.

The results of the division in RA suggest the presence of a dipole anisotropy in Δ. If the angular separation of the radio source and the pole of anisotropy is ϕ, then the magnitude of the dipole term is proportional to $\cos\phi$. A least-squares fit to a dipolar anisotropy yields a pole in the direction ~RA 1320, dec −40°, and a magnitude $\langle\Delta\rangle \simeq (35° \pm 6°)\cos\phi$.

The effect has been sought in other samples[6-8] which together

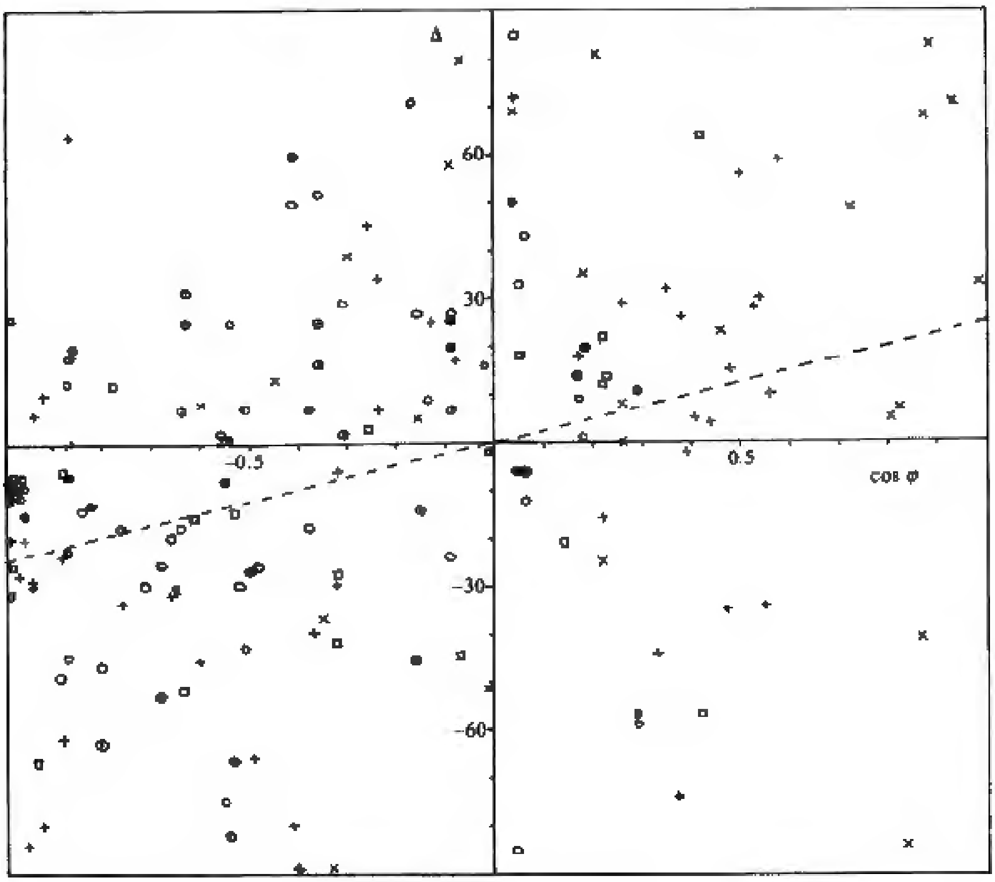

Fig. 1 A plot of Δ against $\cos\phi$: Δ is defined as the position angle of the magnetic field vector minus the position angle of the major axis of the radio source; ϕ is defined as the angular separation on the sky of the radio source and the pole of the dipole anisotropy in Δ, which has been obtained by a least-squares fit to the Δ values plotted. Here, the pole position is RA 14 h 55 min, dec −35°; and the expected magnitude of Δ is given by the dotted line, $\langle\Delta\rangle = 25° \cos\phi$. Also plotted are values of Δ_0 which is the position angle of elongation of the components minus the position angle of the major axis of the source. The symbols for the four samples are: PB sample, +; Laing[6] sample, ○ and (for Δ_0) ⊙; Ekers[7] sample, ×; and Conway[8] sample, □.

cover most of the sky with the exception of the galactic plane. It does not appear that the manner in which the sources were originally selected for the samples can have introduced any position-dependent bias of position angles. The values of Δ for each of the three new independent samples, derived using published polarization measurements[3], are listed in Table 1. When divided at RA 0915 and 2115, and tested against the dipole model given above, they confirm it at high levels of significance. Not only do the values of $\bar{\Delta}$ differ from zero and each other, they do so in the way predicted by the model; this is particularly striking in the southern sample, for which the RA dependence is markedly different from the northern sample.

Thus these other samples clearly confirm the existence of a dipole anisotropy in Δ; the probability of this result arising by chance is very small.

We have searched for systematic errors that could explain this effect. A systematic calibration error could make $\bar{\Delta} \neq 0$, but could not reproduce the variation with position on the sky. The effect is about equal to the correction for ionospheric and galactic Faraday rotations and much larger than their uncertainty of a few degrees; since there was no ambiguity in the magnitude of the rotation measures, it is hard to see how any residual errors could be systematic and RA dependent. The direction of the pole of anisotropy is near (l 320°, b +20°) in galactic coordinates; this suggests that the effect is not of galactic origin, as this direction does not correspond to the direction of the galactic magnetic field[9], nor to the axis of rotation ($b = 90°$), nor to any other obvious physical axis.

Table 1 Magnetic field offset angles for radio sources

Source	Δ	Source	Δ	Source	Δ	Source	Δ
***a* PB Sample from 3CR**							
0017+15	−34	0459+25	−62	1158+31	−16	1618+17	+10
0031+39	+64	0659+25	−46	1232+21	+4	1622+23	+15
0107+31	+10	0802+24	−89	1241+16	+56	1626+39	+5
0123+32	−29	0824+29	−40	1251+15	+28	1627+23	−35
0125+28	−30	0903+16	+25	1251+27	−74	1726+31	+29
0132+37	−20	0905+38	−6	1308+27	−2	2141+27	−80
0133+20	−80	0927+36	+45	1350+31	+26	2145+15	−30
0154+28	−28	0936+36	+7	1420+19	+59	2203+29	−66
0220+39	−20	0938+39	+34	1529+35	−44	2318+23	−32
0300+16	−84	0958+29	+17	1545+21	+30		
0307+16	+6	1108+35	+72	1553+20	−34		
0453+22	−24	1142+31	+18	1615+32	+32		
***b* Laing sample[6] from 3CR**							
0013+79	−26	0605+48	−47	1140+22	−59	1704+61	+71
0017+15	−18	0651+54	−30	1142+31	+9	1825+74	+50
0040+51	−45	0733+70	−18	1157+73	−18	1832+47	−24
0106+13	−14	0809+48	+25	1206+44	−85	1842+45	+27
0154+28	−7	0833+65	−75	1254+47	+43	1845+79	−26
0210+86	−52	0835+58	−30	1258+40	+1	1939+60	+52
0229+34	−8	0850+14	+27	1409+52	+85	2104+76	+2
0410+11	+13	0855+14	+9	1441+52	+33	2153+37	−43
0415+37	−9	1030+58	+29	1609+66	+50	2318+23	−20
0459+25	−49	1111+40	+16	1658+47	−12		
***c* Ekers sample[7] from the southern sky**							
0043−42	90	0431−133	+8	1358−11	+83	1737−60	+5
0114−47	+58	0511−30	+39	1413−36	+33	2040−26	90
0242−57	+69	0518−45	90	1556−21	+71	2058−28	0
0336−35	−89	0618−37	+80	1602−63	−41	2104−25	+81
0334−34	−37	0634−20	+8	1610−608	+68	2153−69	+23
0349−27	+13	0819−30	+35	1637−77	+49	2317−27	+5
0427−53	−51	1211−41	−84	1733−56	+7	2356−61	−25
***d* Conway sample[8] from 4C**							
0035+38	−6	0349+26	−9	1029+25	+18	1333+27	+64
0128+25	−68	0658+35	−31	1100+37	−2	1634+26	−37
0211+34	−32	0733+29	−15	1123+30	−21	2239+33	−16
0214+27	−26	0840+29	−42	1158+25	−58	2356+27	+12
0229+35	−11	0854+34	−28	1253+37	+12		
0241+29	+26	0931+39	+3	1257+38	+13		
0313+34	−7	0950+25	−45	1301+38	+22		

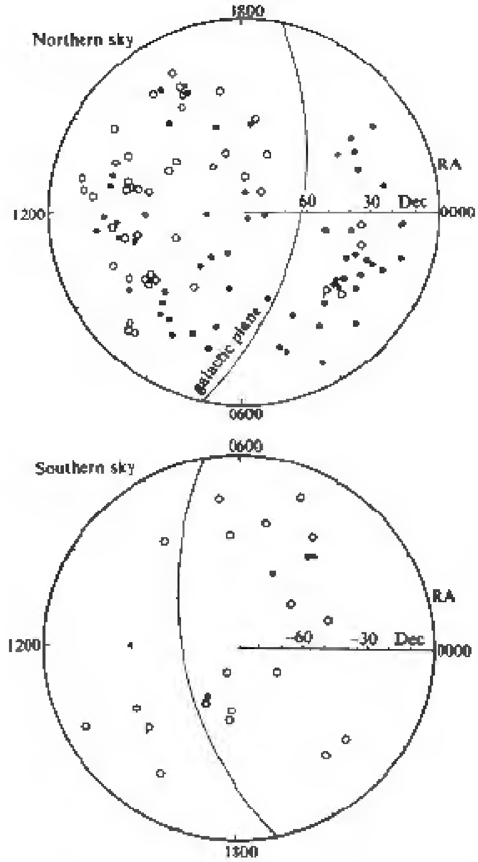

Fig. 2 This diagram shows the source positions in right ascension and declination. Sources with negative Δ are plotted as ● whereas those with positive Δ are plotted as ○. Δ is defined as the position angle of the magnetic field vector minus the position angle of the major axis of the radio source. The positions of the poles of anisotropy are marked P.

So far the analysis has been concerned with the magnetic field configuration in radio sources. It is, however, known[10] that in high luminosity radio sources the magnetic field orientation tends to follow the contours of brightness (an effect explained by anisotropic compression or shear[11]). The difference between the position angles of elongation of individual components (the direction of the 'tails') and of the major axis of the source Δ_t, might therefore be expected to show the same anisotropy as is found in the values of Δ (if this is caused by shearing or compression of the components). Maps of sufficient sensitivity and resolution to obtain accurate values of Δ_t (for a considerable number of sources) were only available for the Laing sample (out of the four samples in Table 1); using the published data[6], values of Δ_t were derived for 30 of Laing's sources (Table 2). For these sources, divided at RA 09 h 15 min and 21 h 15 min, the model predicts $\Delta_1 = -17.4°$, $\Delta_2 = +1.7°$ and $\Delta_t \simeq \Delta$, whereas the mean values of Δ_t obtained are:

$$\text{Sample 1:} \quad \bar{\Delta}_{t1} = -16.9° \pm 8.1°$$

$$\text{Sample 2:} \quad \bar{\Delta}_{t2} = +\ 8.9° \pm 5.7°$$

These values agree with the prediction, and differ from each other as predicted with $\alpha \simeq 4.0 \times 10^{-3}$. Thus the same effect appears to be present at a similar level of significance. This is important because the values of Δ_t do not depend on polarization measurements and are subject to entirely different kinds of error; this rules out explanations based on errors in deriving the magnetic position angles.

The data in Tables 1 and 2 can be brought together into a single sample, which covers most of the sky (~80%). It is well-sampled from a redshift $z \simeq 0.03$ to $\simeq 1.5$, and when the

data are split into high and low z samples the effect is present in both; no correlation with redshift is observed. The effect is also present equally for radio galaxies and for quasars. All 132 sources were used to refine the estimate of dipole anisotropy by a least-squares fit as above; the overall mean pseudo-vector offset is found to be:

$$\langle\Delta\rangle = (25° \pm 5°),\ \mathrm{RA}\ (14\ \mathrm{h}\ 55\ \mathrm{min} \pm 30\ \mathrm{min}),\ \mathrm{dec}\ (-35° \pm 5°)$$

The individual values of Δ and Δ_t are plotted against $\cos\phi$ in Fig. 1: the effect is clearly visible as an excess of points in the first and third quadrants. For the same sources Fig. 2 shows the positions on the sky and the sign of Δ; the dipole anisotropy is evident as an excess of negative values around the pole in the northern sky and of positive values around the opposite pole. Standard statistical tests of correlation have been applied to Fig. 1, taking due account of the number of degrees of freedom available in choosing the dipole axis; they yield a significance level, $\alpha \approx 10^{-8}$.

An explanation for this phenomenon must involve anisotropy on a cosmic scale (over 10 Gpc or more), yielding a preferred orientation of widely separated radio sources. The phenomenon consists of a handedness in the (magnetic) outline, such that sources tend to look S-shaped in one half of the sky and like the mirror image of an S in the other. This can only be explained by a pseudo-vector rather than a true vector or symmetric tensor effect. Possible causes of the pseudo-vector phenomenon appear to be limited to (1) large-scale magnetic fields, or (2) large-scale or universal rotation.

Table 2 Offset angle of elongation of outer components

Source	Δ_t	Source	Δ_t	Source	Δ_t	Source	Δ_t
Laing sample[6] from 3CR							
0013+79	−53	0459+25	+20	1140+22	+11	1832+47	+25
0040+51	+18	0605+48	−63	1142+31	+14	1842+45	+20
0106+13	−13	0733+70	+7	1157+73	+7	1845+79	−26
0154+28	−8	0809+48	−82	1258+40	+20	1939+60	+16
0210+86	+31	0833+65	−8	1609+66	−6	2104+76	+2
0229+34	−8	0835+58	−67	1658+47	−6	2153+37	+7
0410+11	−8	0850+14	−46	1704+61	−14		
0415+37	−15	1030+58	+1	1825+74	+60		

For 22 of these sources, component position angles were obtained from Laing's Table 7 (ref. 6); for the remainder the position angles were taken from the maps. The effect is still present if only Laing's tabulated position angles are used ($\alpha = 0.037$)

Measurements of the Faraday rotation of extragalactic radio sources have been used to place limits on the magnitude of a universal magnetic field[12], which suggests that it would be far too weak to affect the sources' morphology directly. Furthermore, such a field could only produce a pseudovector effect through the inherent asymmetry between electrons and protons, so that strong electric fields and charge separation would be required. A viable explanation along these lines appears unlikely.

An alternative and attractive explanation is that the radio sources rotate relative to the intergalactic medium, the axis of rotation being preferentially aligned with a universal vorticity; for, if the Universe has net angular momentum, this will be conserved and provide a natural axis of rotation aligned over cosmic scales. Considering representative models in which slowly rotating radio galaxies, preferentially aligned, are assumed to have condensed from the intergalactic medium under constant angular momentum, the appropriate angular velocity of the Universe is found to be of the order of 10^{-13} rad yr^{-1}. This value is obtained by considering the overall angular momentum of the radio galaxies and the intergalactic medium, and the mean density of the Universe, to determine the mean vorticity.

A vorticity on a smaller scale, in the range of scale size $1 \leq z \leq 1{,}000$, might provide an alternative explanation for the alignments. It would, however, impose radial velocities of order 300 km s^{-1} on the microwave background, which would have been detected[13,14]. Note that, in the past, such large-scale vorticity has been somewhat loosely called 'rotation of the Universe', and stringent limits have been placed on the maximum allowable vorticity[13–16]. By contrast, a pure universal rotation would produce a pure quadrupole anisotropy[15] well below observational limits[15,16].

Thus there appears to be strong evidence that the Universe is anisotropic on a large-scale, producing position angle offsets in the polarization and brightness distributions of radio sources. These can probably be explained by a rotation of the Universe, with an angular velocity pseudo-vector:

$$\omega_u = (\sim 10^{-13}\ \mathrm{rad\ yr^{-1}}),\ \mathrm{RA}\ (2\ \mathrm{h}\ 55\ \mathrm{min} \pm 30\ \mathrm{min}),\ \mathrm{dec}\ (35° \pm 5°)$$

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